Optimizing Irrigation of Fresh Market Tomato Grown in the Mid-Atlantic United States

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ADDITIONAL INDEX WORDS. drip irrigation, polyethylene mulch, tensiometer, Virginia

SUMMARY. Determining irrigation requirements for fresh market tomato (*Solanum lycopersicum*) production is essential to obtain optimum yields, cost-effective water use, and minimize nitrate leaching. The objective of this study was to determine the appropriate irrigation rate for polyethylene-mulched fresh market tomato grown in Virginia. This study investigated irrigation regimes by applying water based on evapotranspiration (ET) calculations in three spring and three fall seasons. Plants were grown using $0.0 \times ET$, $0.5 \times ET$, $1.0 \times ET$, $1.5 \times ET$, and $2.0 \times ET$. Additional irrigation treatments involved tensiometers installed at 12-inch depth in the bed, programmed to irrigate at soil moisture set points of -20 , -40 , and -60 kPa. Tensiometer treatments were able to irrigate up to nine times per day if soil moisture fell below the designated moisture set point. Measurements included fruit yield, plant and fruit nitrogen (N) uptake, and inorganic soil nitrate-N (NO_3-N) at 0 to 10-, 10 to 20-, and 20 to 30-inch depths. Overall, the $0.5 \times ET$ treatment provided optimum yields in all growing seasons except Spring 2010, which was unseasonably hot and dry. A tensiometer treatment (-40 kPa) provided optimum yields in all growing seasons, and was able to adjust irrigation in a hot and dry season. Residual soil NO_3-N at 0 to 10 inches generally exhibited an inverse relationship with yield; greater yields resulted in less residual soil NO_3-N . In most treatments throughout the duration of this study, plant N uptake + fruit N uptake accounted for most of the N fertilizer applied (68% to 151%). In conclusion, an irrigation rate of $0.5 \times ET$ and a tensiometer treatment (-40 kPa) provided minimal irrigation inputs to obtain optimum marketable yields while also minimizing residual soil nitrate that may be prone to leaching after the season.

Tomato is an extensively grown vegetable crop on the Eastern Shore of Virginia (Accomack and Northampton counties). In 2011, 4600 acres of commercial fresh market tomato were harvested in Virginia, with an estimated value of \$47.5 million [U.S. Department of Agriculture (USDA), 2013]. Commercial producers in the United States harvested a total of 94,210 acres of fresh market tomato plants with Virginia ranked third in harvested acreage after California

and Florida [32,000 and 28,500 acres, respectively (USDA, 2013)]. In regards to value of production, Virginia ranked fourth behind Florida, CA, and North Carolina [\$435, \$259, and \$53 million, respectively (USDA, 2013)]. With so many acres dedicated to tomato grown in close proximity to the Chesapeake Bay and tributaries leading to the bay, nitrate leaching and runoff are of great concern.

Drip irrigation combined with polyethylene mulch is a common

practice for commercially grown fresh market tomato in the mid-Atlantic United States. Drip irrigation and polyethylene mulch systems reduce evaporation and therefore increase water use efficiency on coarse soils with low water-holding capacities, among many other benefits (Hochmuth et al., 2012; Zotarelli et al., 2009a). Coarse sandy soils have water-holding capacities of 8% to 15%, while fine textured soils may have water-holding capacities over 40% (Locascio, 2005). With a lower water-holding capacity in coarse soils, proper irrigation is necessary to obtain optimum yield, uphold cost-effective water use, and reduce the propensity for dissolved nutrients to leach (Zotarelli et al., 2009b). Determining suitable timing and quantity to irrigate is essential for efficient crop production. Stanley and Clark (2004) suggested irrigating with frequent short durations using drip irrigation on soils with low water-holding capacities to reduce water loss.

A crop's water requirement is determined by the ET that takes place from the system. Evapotranspiration is a measurement of water loss from the cropping system that occurs through two processes: 1) evaporation from the soil surface and 2) transpiration from plant leaves; this amount directly relates to the plant's water need. Irrigation requirements are equal to the amount of water lost through ET minus water deposited through precipitation (Allen et al., 1998; Doorenbos and Pruitt, 1977). In situ measurements of actual soil moisture can also be used to determine when irrigation is needed. Smajstrla et al. (1997) discussed irrigation scheduling on sandy soils in Florida and suggested using a tensiometer

We would like to thank the funders of this project, Virginia Department of Agriculture Specialty Crop Competitive Grant Program, for helping to make this research possible. We would also like to thank the staff at the Virginia Tech Eastern Shore Agricultural Research and Extension Center in Painter, Virginia, for their help, hard work, and dedication to this project.

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.4047	acre(s)	ha	2.4711
102.7902	acre-inch(es)	m ³	0.0097
100	bar	kPa	0.01
1	cbar	kPa	1
0.3048	ft	m	3.2808
9.3540	gal/acre	L·ha ⁻¹	0.1069
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
0.4536	lb	kg	2.2046
1.1209	lb/acre	kg·ha ⁻¹	0.8922
0.0254	mil	mm	39.3701
1	ppm	mg·kg ⁻¹	1
1	ppm	mg·L ⁻¹	1
(°F - 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

that provided a direct measurement of soil matric potential at the installed depth. In addition to calculated ET that determined the amount to irrigate, a tensiometer can indicate when to irrigate.

A study performed by Locascio and Smajstrla (1996) examined calculated irrigation rates and tensiometer-based treatments and applied multiple rates of irrigation based on calculated pan-evaporation to polyethylene-mulched tomato on a fine sandy soil near Gainesville, FL. They observed in dry years, quantities between $0.5 \times$ and $1.0 \times$ pan-evaporation produced maximum yields. Pan-evaporation is a measurement of the rate of water lost via evaporation from a U.S. Weather Service Class A pan. Maximum production was obtained by using a tensiometer scheduled to initiate irrigation at -10 kPa, with a water output of $0.35 \times$ pan-evaporation. Soil samples (0 to 15 cm) taken throughout the growing seasons showed that in treatments receiving irrigation, water quantity did not influence water extractable nitrogen [nitrate-N + ammonium-N ($\text{NH}_4\text{-N}$)]. However, a 0-water treatment did result in greater water extractable N than all irrigated treatments, likely due to lesser yields in two out of three growing seasons. The tensiometer treatment extractable soil N values were similar to the average of all irrigated treatments. Marketable yield in the tensiometer treatment was not significantly different from $0.75 \times$ pan-evaporation yield in all three growing seasons.

Evapotranspiration for a specific crop (ET_c) is calculated by multiplying a reference ET (ET_o) by the appropriate crop coefficient (K_c):

$$\text{ET}_c = \text{ET}_o \times K_c \quad [1]$$

Reference ET is based on a hypothetical grass surface that is only affected by climatic conditions; soil conditions are not considered. The Food and Agriculture Organization of the United Nations (FAO) suggested the use of the Hargreaves equation:

$$\begin{aligned} \text{ET}_o = 0.0023 \times (T_{\text{mean}} + 17.8) \\ \times (T_{\text{max}} - T_{\text{min}})^{0.5} \times R_a \end{aligned} \quad [2]$$

to calculate the hypothetical grass surface ET_o , where ET_o = reference ET, T_{mean} = mean temperature (degrees

Celsius), T_{max} = maximum temperature (degrees Celsius), T_{min} = minimum temperature (degrees Celsius), and R_a = extraterrestrial solar radiation (millimeters per day) (Allen et al., 1998).

The use of drip irrigation and polyethylene mulch decreases evaporation from the field system and therefore decreases the K_c (Allen et al., 1998; Amayreh and Al-Abed, 2005). These values are associated with increasing canopy growth and associated increased transpiration. K_c is a unitless ratio of ET_c/ET_o that can be found in several FAO publications (Allen et al., 1998; Doorenbos and Pruitt, 1977) for vegetables, forages, fruit trees, and other crops. The value varies based on crop, growth stage, and management practices (Smajstrla et al., 1997). Most crop coefficients range from 0.5 to 1.2 with larger values during midseason ($K_{c \text{ mid}}$) growth as water requirements are increased, and lower values during initial ($K_{c \text{ ini}}$) and late-season ($K_{c \text{ end}}$) growth as water requirements decrease. Haddadin and Ghawi (1983) studied the effect of polyethylene mulch on field-grown tomato on sandy loam soil in the Jordan Valley of Israel and found that the use of black plastic mulch significantly increased yield and water use efficiency. The FAO reported that Haddadin and Ghawi's (1983) research found a reduction of K_c by 35% for tomato when using polyethylene mulch with drip irrigation (Allen et al., 1998). Amayreh and Al-Abed (2005) found similar results with a 36% reduction in K_c over the entire growing season for polyethylene mulched, drip-irrigated tomato grown on a silty clay soil in the Jordan Valley. More specifically, Amayreh and Al-Abed (2005) found a 35% reduction of K_c in the development stage (initial and crop development stages), a 31% reduction of $K_{c \text{ mid}}$, and a 40% reduction of $K_{c \text{ end}}$. Reducing K_c decreases the calculated volume of water to apply to crops and may reduce nutrient leaching attributable to excess irrigation.

If nutrients leach below the effective root zone, they will not be absorbed by the plant and are lost from the production system, reducing fertilizer use efficiency. Machado and Oliveira (2005) reported that rooting depth of tomato in sandy soil was independent of three different

water regimes and three different drip irrigation depths. Zotarelli et al. (2009b), observed tomato root systems under several irrigation treatments on sandy soil near Citra, FL. Root distribution patterns showed that independent of irrigation treatment, root length density concentrated around drip tape emitters. Zotarelli et al. (2009b), Oliveira et al. (1996), and Machado and Oliveira (2005) agree that the majority of tomato roots are concentrated in the upper 40 cm of the soil profile. Therefore, nutrient movement below 40 cm has exited the effective root system of tomato, and consequently, the production system.

Ideally, an optimal irrigation regime limits the amount of fertilizer leached below the root zone and conserves irrigation water usage, while providing optimum marketable yields. The objective of this study was to determine an optimal irrigation regime for polyethylene-mulched fresh market tomato grown on a sandy loam soil in the mid-Atlantic United States.

Materials and methods

This study was established in the spring and fall seasons of 2009, 2010, and 2011 (six site seasons) on a Bojac sandy loam (coarse-loamy, mixed, semiactive, thermic Typic Haplu-dults) (USDA, 2002) at the Virginia Tech Eastern Shore Agricultural Research and Extension Center in Painter, VA (lat. 37.59°N , long. 75.77°W). Bojac sandy loam has $\approx 59\%$ sand, 30% silt, and 11% clay in the Ap horizon (0 to 18 inches). The soil was conventionally tilled, and 8-inch raised beds were constructed on 6-ft centers. In a single pass, beds were fumigated with methyl bromide and chloropicrin [67:33 (w/w)] at the rate of 300 lb/acre, and 1.25-mil-thick polyethylene mulch was applied over the bed. Under the mulch, drip tubing was deployed (Aqua-Traxx; Toro, Riverside, CA) with emitters spaced 12 inches apart and a delivery rate of 5.6 L/100 m per minute at 0.55 bar was placed 3 to 4 inches from the bed center. Four to 5-week-old tomato seedlings ('BHN 602'; BHN Seed, Immokalee, FL) were transplanted on 18-inch in-row spacings, resulting in a plant population density of ≈ 4840 plants/acre. Tomato seedlings were transplanted in 40-ft single row plots on 20 May 2009, 21 May

2010, and 25 May 2011, for the spring season and on 17 July 2009, 13 July 2010, and 28 July 2011, for the fall season. All other production practices were conducted according to Wilson et al. (2012).

CALCULATING ET. We calculated ET_c by multiplying K_c by ET_o (Eq. [1]). Described by Allen et al. (1998), ET_o was determined using the Hargreaves equation via temperature and extraterrestrial solar radiation. A 1971–2000 Monthly Climate Summary from the Southeast Regional Climate Center (2007) for Painter, VA (lat. 37.35°N, long. 75.49°W) provided monthly minimum and maximum temperature values. Extraterrestrial solar radiation for Painter, VA, was found from Table 2.6 of Allen et al. (1998) by using an estimated latitude of 38°N.

To calculate ET_c for different growth stages, K_c was interpolated from Doorenbos and Pruitt (1977) and Allen et al. (1998). The K_c for tomato was estimated at 0.60 for $K_{c\text{ ini}}$ (Allen et al., 1998), and $K_{c\text{ mid}}$ and $K_{c\text{ end}}$ values of 1.05 and 0.60 (Doorenbos and Pruitt, 1977), respectively. The K_c value during the crop development ($K_{c\text{ CD}}$) stage was estimated to be 0.83, an average of the values used for $K_{c\text{ ini}}$ and $K_{c\text{ mid}}$. The progression of K_c throughout the growing season was $K_{c\text{ ini}}$, $K_{c\text{ CD}}$, $K_{c\text{ mid}}$, and finally $K_{c\text{ end}}$. Crop growth stage was based on physiological maturity of the plant to account for varying growth advancements per season (Allen et al., 1998). Crop coefficient values were reduced accordingly in calculating ET_c over the growing season because of the use of polyethylene mulch. Crop coefficients during initial growth stage, crop development stage, and midseason stage were reduced by 35%, 35%, and 31%, respectively (Amayreh and Al-Abed, 2005).

CALCULATING IRRIGATION. Irrigation needed for a crop is ET_c minus precipitation (Allen et al., 1998; Doorenbos and Pruitt, 1977). Long-term average precipitation data were used from the Southeast Regional Climate Center (2007). A 1971–2000 Monthly Climate Summary for Painter, VA, was used for average monthly total precipitation estimates. Historical rainfall data were used to calculate average daily precipitation and subtracted from ET_c to determine daily irrigation for

respective month and growth stages of the crop. Irrigation calculated by subtracting precipitation from ET_c , as defined by Doorenbos and Pruitt (1977) and Allen et al. (1998), was labeled as treatment “1.0×ET” in this study.

IRRIGATION TREATMENTS. Irrigation treatments were set using automatic timers (Hunter Smart Valve Controller, San Marcos, CA). The total calculated daily watering time per treatment was halved to irrigate twice a day, and applied 7 d per week, to deliver $0.0 \times ET$, $0.5 \times ET$, $1.0 \times ET$, $1.5 \times ET$, and $2.0 \times ET$. Irrigation for the tensiometer treatments was triggered automatically with a wired tensiometer (model RA; Irrometer, Riverside, CA) installed in the active root zone (12-inch depth). One wired tensiometer was used to trigger irrigation for all four replications. Several other tensiometers were installed in treatments to verify the wired tensiometer readings in the respective treatments. Irrigation for the tensiometer treatments (Tens-20, Tens-40, and Tens-60) initiated after the tensiometer's reading raised above preset values of -20, -40, or -60 kPa, respectively, based on the treatment (only a -40 kPa value was used in 2009). An automatic timer wired into the tensiometer/irrigation system switched irrigation on for a maximum possibility of nine times per day. Each of the nine possible irrigation periods were set for the duration of time calculated for daily $0.5 \times ET$. This gave the possibility of the automatic tensiometer system to water between $0.0 \times ET$ and $4.5 \times ET$.

Irrigation outputs were measured by cumulative water application on four replications for each treatment. A water meter (C700; Elster AMCO Water, Ocala, FL) was installed for each treatment, and cumulative water output was recorded weekly throughout the season.

The overall experimental design was a randomized complete block design that had treatments replicated four times, giving a total plot combination of 20 plots in Spring 2009 ($0.5 \times ET$, $1.0 \times ET$, $1.5 \times ET$, $2.0 \times ET$, and Tens-40), 24 plots in Fall 2009 ($0.0 \times ET$, $0.5 \times ET$, $1.0 \times ET$, $1.5 \times ET$, $2.0 \times ET$, and Tens-40), and 32 plots ($0.0 \times ET$, $0.5 \times ET$, $1.0 \times ET$, $1.5 \times ET$, $2.0 \times ET$, Tens-20, Tens-40, and Tens-60) in both spring and fall seasons of 2010 and 2011.

FERTILIZER APPLICATION. A total of 200 lb/acre N was applied over the growing season. A preplant rate of 86 lb/acre N using ammonium nitrate (34N-0P-0K) was incorporated into the plant beds using a rotary tiller before laying polyethylene mulch. The remaining N (114 lb/acre N) was applied using liquid urea-ammonium nitrate (32N-0P-0K) through biweekly fertigation throughout the growing season during prescheduled irrigation events. Nitrogen rates used in fertigation increased as the growing season progressed to match plant N uptake (Wilson et al., 2012). Fertilized N was applied at 0.50, 0.70, 1.00, 1.50, 2.20, and 2.43 lb/d N for time periods 0–14, 15–28, 29–42, 43–56, 57–77, and 78–98 d after transplanting, respectively. All treatments received the same amount of N fertilizer before planting and throughout biweekly fertigation. Additionally, phosphorus and potassium fertilizers were applied equally to all treatments based on soil test results (Maguire and Heckendorn, 2011).

PETIOLE SAP NO_3 -N. Petiole sap NO_3 -N tests were performed when fruit were ≈ 2 inches in diameter. Petioles were collected from six plants per plot from the upper most fully expanded leaf (Hochmuth, 1994; Ozores-Hampton et al., 2012) between 10:00 AM and 12:00 PM. The sap of all six petioles was combined, and NO_3 -N concentrations were found using a Cady meter (Spectrum Technologies, Plainfield, IL).

YIELD. Yield was calculated by harvesting mature green fruit two to three times, depending on the season, which is the standard agronomic practice. Fruit were separated by size according to USDA standards (USDA, 1991) and weighed. Medium, large, and extralarge fruit weights were combined to determine marketable yield.

POSTHARVEST SAMPLING. After harvest termination, plant, fruit, and soil samples were collected. One plant per plot was collected, dried, and weighed to estimate total aboveground biomass. Plant samples were ground and analyzed for total N via combustion (Bremner, 1996) (vario EL cube; Elementar Americas, Mt. Laurel, NJ) to determine plant N concentrations. Nitrogen concentration in the plant material was subsequently multiplied by plant biomass to determine total aboveground N uptake in the plant.

Five fruit from each plot were collected, dried, ground, and analyzed for total N via combustion (vario EL cube) to determine fruit N concentration. Nitrogen concentrations in the fruit material were multiplied by fruit biomass to determine total above-ground N uptake in the fruit. Fruit were assumed to contain 94% water (Angelini and Magnifico, 2010). Therefore, total yield was multiplied by 6% to determine fruit biomass. Plant and fruit N concentrations multiplied by total aboveground biomass and total fruit yield, respectively, determined total system (plant + fruit) N uptake. Nitrogen use efficiency of applied fertilizer (FNUE) was calculated as total system N uptake divided by total N applied via fertilizer, multiplied by 100.

Soil samples from 0 to 10-, 10 to 20-, and 20 to 30-inch depths were collected. For each depth, two cores were taken on the side of the bed opposite of the drip tape, and four cores on the side of the bed with the drip tape; two between the drip tape and the edge of the bed and two between the drip tape and the center of the bed. Soil samples were air dried and ground. Soils were extracted with 2 M potassium chloride (KCl) at a 1:10 soil:2 M KCl ratio, shaken for 1 h, and filtered (Mulvaney, 1996). Extracts were analyzed within 24 h for nitrate-N + nitrite-N colorimetrically using a continuous flow analyzer (Lachat QuickChem 8500; Hach Co., Loveland, CO).

STATISTICS. Statistical analysis was conducted with JMP (version 9; SAS Institute, Cary, NC). An analysis

of variance was performed and if significance was present ($P < 0.10$), separation of means was conducted using Student's t least significant difference (LSD) values established at $\alpha = 0.10$ ($LSD_{0.10}$). Season was significant for all data sets; therefore, all data were analyzed individually by season.

In Spring 2009, treatments $2.0 \times$ ET and the tensiometer treatment (Tens-40) encountered excessive pressure in the drip tubing and were inflicted with large leaks in the plots. Therefore, these treatments were removed from statistical analysis due to the confounding circumstances.

Results and discussion

IRRIGATION RATES. Season-long irrigation and season length can be seen in Table 1. Readings for Fall 2009 were not available. Treatment $0.0 \times$ ET applied between 0.4 and 1.4 acre-inches of water through fertigation practices. Irrigation rates in calculated ET treatments varied between seasons because of physiological maturity progress of the plants and length of season.

Tensiometer treatments did not apply water as we expected (Tens-20 > Tens-40 > Tens-60). Many season-long adjustments needed to be made to accommodate the liquid in the tensiometer and ensure it did not dry out. Additionally, the wetting fronts from the drip tape emitters greatly impacted the necessary placement of the tensiometers in the bed and subsequent readings. Because of the disturbance of the soil when creating beds, soil structure and soil pores are altered, and therefore, the

wetting front may vary. Overall, we believe the use of tensiometers in drip-irrigated fresh market tomato fields provides essential data on soil matric potential and can indicate when irrigation is needed. Data are included for all tensiometer treatments; however, using wired tensiometers to autoinitiate drip irrigation warrants further research.

YIELD. In Spring 2009, $0.5 \times$ ET and $1.0 \times$ ET yielded significantly more marketable fruit than $1.5 \times$ ET (63,331; 60,663; and 44,153 lb/acre marketable fruit, respectively) (Table 2). In Fall 2009, Tens-40 yielded similar to $0.5 \times$ ET (44,686 and 39,549 lb/acre marketable fruit, respectively). However, out of the calculated irrigation treatments, $0.5 \times$ ET was similar to $1.0 \times$ ET and $1.5 \times$ ET and greater yielding than $0.0 \times$ ET and $2.0 \times$ ET.

In Spring 2010, $1.5 \times$ ET, $2.0 \times$ ET, and Tens-40 produced the greatest yields with 48,188; 41,364; and 42,496 lb/acre marketable fruit, respectively (Table 2). $0.0 \times$ ET resulted in significant yield loss, producing significantly less marketable yield than every other treatment. The Spring 2010 season was hotter and had less cumulative precipitation in May, June, and July than 2009, 2011, and the 30-year average (Fig. 1). Because of the unseasonably hot dry season, it was expected that higher calculated ET treatments would result in greater yields. In Spring 2010, the higher calculated irrigation treatments ($1.5 \times$ ET and $2.0 \times$ ET) were not significantly different from the Tens-40 treatment, showing that the use of a tensiometer set at -40 kPa might protect yields in hotter and dryer growing seasons compared with calculated ET values. In a sandy loam, soil is at field capacity at -10 to -20 kPa and at -40 to -60 kPa, 50% of available water is depleted (Wilson et al., 2012). Treatments $1.5 \times$ ET, $2.0 \times$ ET, and Tens-40 applied similar amounts of irrigation in Spring 2010 (Table 1). In Fall 2010, there were no significant differences between treatments and average yield was 29,318 lb/acre marketable fruit.

In Spring 2011, $0.0 \times$ ET produced significantly less marketable fruit than every other treatment. There were no other significant differences in Spring 2011 between other irrigation treatments. In Fall 2011,

Table 1. Season-long irrigation for fresh market tomato grown on a Bojac sandy loam soil in 2009, 2010, and 2011.

Treatment ^a	2009		2010		2011	
	Spring	Fall ^b	Spring	Fall	Spring	Fall
	Irrigation (acre-inches) ^c					
$0.0 \times$ ET	—	—	1.4	0.5	0.4	0.4
$0.5 \times$ ET	6.5	—	5.7	2.5	5.5	3.1
$1.0 \times$ ET	12.2	—	9.9	5.4	12.1	3.9
$1.5 \times$ ET	16.3	—	17.6	7.8	12.8	5.7
$2.0 \times$ ET	—	—	17.1	7.6	16.0	5.7
Tens-20	—	—	5.7	10.7	14.0	3.5
Tens-40	—	—	17.3	5.0	9.9	3.8
Tens-60	—	—	3.9	13.9	9.5	1.8
Season length (d) ^w	82	89	80	80	79	109

^aET = evapotranspiration; Tens = tensiometer treatments set at -20 , -40 , and -60 kPa, respectively; 1 kPa = 1 cbar.

^bReadings not available for Fall 2009 season.

^c1 acre-inch = 102.7902 m³.

^wDays from transplant to final harvest.

Table 2. Marketable yield for fresh market tomato grown on a Bojac sandy loam soil in 2009, 2010, and 2011.

Treatment ^z	2009		2010		2011	
	Spring	Fall	Spring	Fall	Spring	Fall
Marketable yield (lb/acre) ^y						
0.0 × ET	—	28,979 c	2,094 f	31,998 NS	22,888 b	29,640 NS
0.5 × ET	63,331 a ^x	39,549 ab	20,110 e	36,500	55,938 a	26,650
1.0 × ET	60,663 a	33,505 bc	29,306 cd	26,572	50,312 a	24,718
1.5 × ET	44,153 b	36,185 bc	48,188 a	24,309	56,596 a	26,347
2.0 × ET	—	31,903 c	41,364 ab	23,819	49,979 a	22,427
Tens-20	—	—	34,914 bc	31,563	62,243 a	30,024
Tens-40	—	44,686 a	42,496 ab	28,629	56,168 a	23,809
Tens-60	—	—	27,098 de	31,158	54,112 a	28,790
P value	0.01	0.02	<0.01	0.16	0.04	0.18

^zET = evapotranspiration; Tens = tensiometer treatments set at -20, -40, and -60 kPa, respectively; 1 kPa = 1 cbar.

^y1 lb/acre = 1.1209 kg·ha⁻¹.

^xMeans followed by the same letter, within column, are not significantly different ($P < 0.10$) by Student's t least significant difference test; NS = not significantly different.

there were no significant differences between treatments and yields averaged 26,551 lb/acre marketable fruit.

Overall, marketable yields for all treatments (except 0.0 × ET and

0.5 × ET in Spring 2010) were greater than average Virginia fresh market tomato production for 2009, 2010, and 2011 [30,000; 21,000; and 22,000 lb/acre fruit, respectively

(USDA, 2013)]. Even the 0.0 × ET treatment resulted in yields close to the Virginia averages (besides Spring 2010), likely due to above average June rains in 2009 and 2011 (Fig. 1), and generally cooler and wetter conditions in the fall season. However, weather factors including temperature and rainfall influenced yields in several calculated irrigation treatments, as seen in Spring 2010. In an unseasonably hot and dry growing season, calculating ET via historical averages will not supply sufficient irrigation for optimum yields. Locascio and Smajstrla (1996) saw in very dry seasons, a 0-irrigation treatment (0.0 × ET) resulted in poor plant growth and water application to subsequent treatments significantly increased fruit yield. This is similar to our results in Spring 2010, which was very dry. Although yield in 0.5 × ET was significantly less than higher calculated ET irrigation rates (1.5 × ET

Fig. 1. Temperature (A) and precipitation (B) from Painter, VA during growing seasons of 2009, 2010, and 2011; 30-year averages provided by Southeast Regional Climate Center (2007); $(^{\circ}\text{F} - 32) \div 1.8 = ^{\circ}\text{C}$, 1 inch = 2.54 cm.

was greatest yielding in Spring 2010), a significant increase in yield was observed between $0.0 \times ET$ and $0.5 \times ET$. Additionally, while $0.5 \times ET$ in Spring 2010 produced yields near the average yield for Virginia in 2010 (20,110 and 21,015 lb/acre fruit, respectively) irrigation was a limiting factor on yield as $1.0 \times ET$ resulted in significantly greater yields than $0.5 \times ET$.

In Spring seasons, treatment $1.0 \times ET$ applied ≈ 0.23 inch of water per day at season peak. Peak water applications for treatment $1.0 \times ET$ in fall seasons were 0.13 inch per day. Less irrigation was needed in fall seasons because of milder temperatures and greater average rainfall. The lack of significant differences between treatments in Fall 2010 and Fall 2011 coincides with findings in Locascio and Smajstrla (1996) where marketable yield was unaffected by water application in a season with greater rainfall (averaging 1.3 inches/week) than other seasons, similar to Fall conditions in Virginia.

Incorporating daily weather readings into ET calculations would be beneficial in unseasonable growing conditions. However, producers would be reluctant to continuously vary their irrigation regimes and change irrigation controllers. An alternative to daily ET calculations is to use a tensiometer to monitor soil moisture (Coolong et al., 2011). Our expectation was for $1.0 \times ET$ to provide the optimal rate of irrigation to polyethylene mulched, drip-irrigated fresh market tomato plants grown in Painter, VA; as ET was calculated and K_c was reduced accordingly for the use of polyethylene mulch. However, the calculated $0.5 \times ET$ treatment provided optimum yields in all growing seasons (except Spring 2010) and were even numerically greater in seasons where there were no significant differences in calculated irrigation treatments (Fall 2010 and Fall 2011). Applying $0.5 \times ET$ rate of irrigation accompanied by the use of a tensiometer, with an optimal reading of -40 kPa, will supply sufficient irrigation and provide an in situ measurement of soil water tension to monitor and make adjustments in unseasonable growing seasons. This recommendation is similar to findings by Locascio and Smajstrla (1996) where greatest marketable tomato yields were obtained with $0.75 \times ET$ and was similar to yields obtained using a tensiometer to schedule irrigation.

Additionally, a tensiometer set point of -40 kPa agrees with Coolong et al. (2011) who found a dual-tensiometer-system set at $-45/-40$ kPa used a minimal amount of water while maintaining yields compared with other tensiometer set points.

PETIOLE SAP NO_3 -N. In Spring 2009, $1.0 \times ET$ had significantly higher petiole sap NO_3 -N concentrations than $0.5 \times ET$ [792 and 501 ppm NO_3 -N, respectively ($P = 0.07$, $LSD_{0.10} = 196$)]; while $1.5 \times ET$ (648 ppm NO_3 -N) was not significantly different from either $1.0 \times ET$ or $0.5 \times ET$. Although $0.5 \times ET$ was significantly lower than $1.0 \times ET$, it still falls in the sufficiency range of 400 to 600 ppm NO_3 -N (Hochmuth, 1994). In all subsequent seasons, there were no significant differences in petiole sap NO_3 -N concentrations between treatments. Generally, irrigation did not influence petiole sap NO_3 -N, as sufficient N concentrations were present. Additionally, season averages consistently fell above the suggested sufficiency concentration range of 400 to 600 ppm NO_3 -N (Hochmuth, 1994). Hochmuth (1994) sufficiency petiole sap NO_3 -N concentrations were based on all N fertilizer being applied pre-plant. This study suggests the biweekly application of N fertilizer via fertigation throughout the growing season was the reason for our elevated petiole sap NO_3 -N concentrations.

PLANT NITROGEN CONCENTRATION. Nitrogen concentrations in plant material differed significantly in one growing season: Spring 2010. Treatments $0.0 \times ET$ and $0.5 \times ET$ had significantly more N per unit weight of plant material than all other treatments (33.71 and 30.81 g·kg⁻¹ N, respectively). Treatments $2.0 \times ET$ and Tens-40 had significantly less N per unit weight of plant material than all other treatments. No significant differences were observed in subsequent growing seasons. Averages for Spring 2009, Fall 2009, Fall 2010, Spring 2011, and Fall 2011 were 23.67, 35.29, 37.00, 26.25, and 38.59 g·kg⁻¹ N, respectively. According to standard values for tissue analysis for Florida (Hochmuth et al., 2004), our plant tissue analysis tested mainly in adequate (20 to 30 g·kg⁻¹ N) and high (>30 g·kg⁻¹ N) status levels for harvest period sampling. The lack of significant differences between treatments and

adequate and high plant tissue status levels show that irrigation (neither shortages nor excess) impacted N concentration in plant material.

Plant N uptake (leaves and stems) showed no significant differences in any growing season. Irrigation did not influence total N uptake in the plant. Averages for Spring 2009, Fall 2009, Spring 2010, Fall 2010, Spring 2011, and Fall 2011 were 47.35, 119.75, 73.63, 74.78, 62.18, and 99.54 lb/acre N, respectively. Zotarelli et al. (2009a) observed plant N uptake (leaves and stems) accumulations of 33.9, 43.6, and 53.5 kg·ha⁻¹ N in spring tomato studies conducted in Florida fertilized with 176 kg·ha⁻¹ N. Our fall season plant N uptake values are larger than those found by Zotarelli et al. (2009a) and may be due to larger vegetative growth and less fruit set in these seasons.

FRUIT NITROGEN CONCENTRATION. Nitrogen concentrations in fruit were significantly different between treatments in one growing season: Fall 2010. Treatment Tens-40 had the largest fruit N concentration and was similar to treatments $1.5 \times ET$, Tens-20, and Tens-60. No significant differences were observed in subsequent growing seasons. Averages for Spring 2009, Fall 2009, Spring 2010, Spring 2011, and Fall 2011 were 42.07, 51.88, 46.72, 46.07, and 52.33 g·kg⁻¹ N, respectively.

As expected, significant differences in fruit N uptake (Table 3) paralleled growing seasons with significant differences in marketable yield (Table 2). In Spring 2009, $0.5 \times ET$ and $1.0 \times ET$ had significantly greater fruit N uptake than $1.5 \times ET$. In Fall 2009, $0.5 \times ET$ and Tens-40 had significantly more fruit N uptake than other treatments. In Spring 2010, $1.5 \times ET$, $2.0 \times ET$, and Tens-40 had significantly more fruit N uptake than all other treatments while $0.0 \times ET$ was significantly lower than all other treatments. In Spring 2011, $0.0 \times ET$ was significantly lower than all other treatments. There were no significant differences found in Fall 2010 and Fall 2011. Fruit N uptake for all seasons ranged from 47.50 to 206.34 lb/acre N. This uptake range showed that 24% to 103% of the fertilizer applied (200 lb/acre N) left the farm after harvest. In addition, most fruit N uptake

Table 3. Total nitrogen uptake in fruit biomass for fresh market tomato plants grown on a Bojac sandy loam soil in 2009, 2010, and 2011.

Treatment ^z	2009		2010		2011	
	Spring	Fall	Spring	Fall	Spring	Fall
	Total nitrogen uptake (lb/acre) ^y					
0.0 × ET	—	112.97 c	47.50 d	103.87 NS	106.63 b	136.90 NS
0.5 × ET	151.12 a ^x	145.48 ab	105.05 c	119.43	189.85 a	116.00
1.0 × ET	142.59 a	115.68 c	125.19 bc	88.47	184.29 a	111.65
1.5 × ET	100.62 b	122.66 bc	182.22 a	87.29	178.24 a	117.54
2.0 × ET	—	118.82 bc	167.27 a	83.06	164.15 a	126.32
Tens-20	—	—	127.88 bc	115.50	206.34 a	143.21
Tens-40	—	160.13 a	162.26 a	110.62	200.56 a	116.57
Tens-60	—	—	134.51 b	112.63	200.76 a	143.64
P value	0.02	0.05	<0.01	0.15	0.05	0.16

^zET = evapotranspiration; Tens = tensiometer treatments set at -20, -40, and -60 kPa, respectively; 1 kPa = 1 cbar.

^y1 lb/acre = 1.1209 kg·ha⁻¹.

^xMeans followed by the same letter, within column, are not significantly different ($P < 0.10$) by Student's t least significant difference test; NS = not significantly different.

Table 4. Nitrate-nitrogen concentrations of 2 M potassium chloride-extracted soil sampled at depth after tomato growing season on a Bojac sandy loam soil in 2009, 2010, and 2011.

Treatment ^z	2009		2010		2011	
	Spring	Fall	Spring	Fall	Spring	Fall
	Nitrate-nitrogen concn (mg·kg ⁻¹ soil) ^y					
	0 to 10-inch depth ^y					
0.0 × ET	—	3.68 NS	12.57 a	9.17 a	6.34 a	6.65 a
0.5 × ET	0.33 NS ^x	1.85	6.02 bc	4.74 b	6.96 a	4.92 ab
1.0 × ET	0.29	1.83	10.21 ab	2.28 c	2.31 b	4.06 bc
1.5 × ET	0.26	0.87	3.94 c	3.83 bc	2.63 b	2.40 cd
2.0 × ET	—	1.01	2.32 c	3.40 bc	2.16 b	1.83 cd
Tens-20	—	—	5.14 bc	2.21 c	1.83 b	3.34 bcd
Tens-40	—	1.18	9.72 ab	3.72 bc	3.85 b	1.42 d
Tens-60	—	—	13.70 a	2.98 bc	3.21 b	5.68 ab
P value	0.91	0.27	0.01	<0.01	0.01	0.01
	10 to 20-inch depth					
0.0 × ET	—	2.25 NS	9.46 a	3.56 a	3.81 NS	0.79 NS
0.5 × ET	0.75 NS	1.00	6.05 ab	2.99 ab	3.39	1.59
1.0 × ET	0.86	0.64	4.27 bc	2.16 c	1.88	1.79
1.5 × ET	1.10	0.72	1.20 c	2.20 c	3.18	1.46
2.0 × ET	—	2.30	0.97 c	1.83 c	1.26	1.61
Tens-20	—	—	3.50 bc	1.93 c	4.77	1.03
Tens-40	—	0.70	4.89 bc	2.17 c	4.23	0.57
Tens-60	—	—	4.83 bc	2.39 bc	2.53	1.32
P value	0.36	0.40	0.07	0.02	0.77	0.12
	20 to 30-inch depth					
0.0 × ET	—	1.02 NS	2.76 bc	1.24 NS	1.93 NS	0.55 NS
0.5 × ET	0.48 b	1.02	2.49 cb	1.29	1.99	0.87
1.0 × ET	0.57 b	0.78	3.56 ab	1.13	1.58	1.21
1.5 × ET	1.13 a	0.69	1.08 c	0.92	3.80	0.89
2.0 × ET	—	0.90	1.27 c	0.91	1.41	0.94
Tens-20	—	—	1.68 bc	1.19	1.23	0.54
Tens-40	—	0.45	1.19 c	1.38	2.52	0.44
Tens-60	—	—	4.91 a	1.57	1.17	0.52
P value	0.04	0.17	0.04	0.66	0.67	0.30

^zET = evapotranspiration; Tens = tensiometer treatments set at -20, -40, and -60 kPa, respectively; 1 kPa = 1 cbar.

^y1 mg·kg⁻¹ = 1 ppm; 1 inch = 2.54 cm.

^xMeans followed by the same letter, within column, are not significantly different ($P < 0.10$) by Student's t least significant difference test; NS = not significantly different.

resulted in >50% (100 lb/acre N) capture of N application. Zotarelli et al. (2009a) observed fruit N accumulations of 31.2, 79.3, and 108.2 kg·ha⁻¹ N in three seasons of tomato fertilized with 220 kg·ha⁻¹ N (14% to 48%). Scholberg et al. (2000) found total N accumulation of well managed tomato was 140–200 kg·ha⁻¹ N with roughly 70% of this amount accumulating in the fruit (98 to 140 kg·ha⁻¹ N). The sum of our plant N uptake and fruit N uptake accounted for a large amount of the N fertilizer applied (68% to 151%), and in many treatments, resulted in a FNUE greater than 100%. This large FNUE suggests an additional source of N might be contributing to the system. Irrigation water was tested for inorganic N and resulted in ≈0.036 mg·L⁻¹ NO₃-N and 0.43 mg·L⁻¹ NH₃-N. Applications of 1.0 × ET at peak season (6245 gal/acre per day), irrigation water was applying 0.002 lb/acre per day NO₃-N and 0.022 lb/acre per day NH₃-N (≈0.09 lb/acre NO₃-N and 1.07 lb/acre NH₃-N over the growing season). An additional possible N contribution to the system is high levels of N in the groundwater. Samples collected in shallow wells (4-ft depth) in April and May 2012 contained NO₃-N concentrations ≈20 mg·L⁻¹ NO₃-N.

SOIL SAMPLES. The majority of significant differences between treatments for residual soil NO₃-N (Table 4) were seen at shallow sample depths (0 to 10 inches). Significant differences between treatments in Spring 2009 were only seen at 20 to 30-inch depth, where 1.5 × ET had significantly greater concentrations of NO₃-N than 0.5 × ET and 1.0 × ET. There were no significant differences between treatments at the three sampled depths in Fall 2009. In the unseasonably hot and dry season of Spring 2010, there were significant differences between treatments in all sampled depths. At 0 to 10- and 20 to 30-inch depths, 0.0 × ET had greater concentrations of NO₃-N compared with other calculated irrigation treatments. Tens-60, the least irrigated tensiometer treatment, was similar in NO₃-N concentration to 0.0 × ET at 0 to 10 inch depth, and contained greater concentrations of NO₃-N at 20 to 30 inches than other treatments in Spring 2010. Being such a hot and dry season, this study suggests there was not

enough water applied to treatments $0.0 \times ET$ and Tens-60 to optimize yields (Table 2), and therefore, residual NO_3-N was greater in those treatments. In Fall 2010, significant differences between treatments were observed to 20 inches. As seen in Spring 2010, $0.0 \times ET$ contained significantly more soil NO_3-N than other treatments; however, yields were not significantly different between treatments in Fall 2010. In Spring 2011, and Fall 2011, there were significant differences between treatments in the shallow sampled depth (0 to 10 inches); however, there were no differences at the lower depths (10 to 20- and 20 to 30-inch depths). Generally, as seen in Spring 2010, $0.0 \times ET$ had more soil NO_3-N than other treatments and was statistically similar to $0.5 \times ET$ in Spring 2011 and Fall 2011. A trend of less soil NO_3-N in $0.5 \times ET$ vs. $0.0 \times ET$ was seen in Fall 2009, Spring 2010, Fall 2010, and Fall 2011. The numerically lower concentrations of residual soil NO_3-N in $0.5 \times ET$ vs. $0.0 \times ET$ follows numeric yield increases between the treatments in Fall 2009, Spring 2010, and Fall 2010. This observation was also reported in Locascio and Smajstrla (1996) who observed greater inorganic N ($NO_3-N + NH_4-N$) (0 to 6 inches) (20 and 80 $mg \cdot kg^{-1}$ N) in a 0-water treatment compared with all other irrigated treatments ($0.25 \times ET$ to $1.0 \times ET$) ($<10 \text{ } mg \cdot kg^{-1}$ N) including a tensiometer treatment in two growing seasons. Additionally, the irrigated treatments resulted in significantly greater marketable yields. A residual concentration of 10 $mg \cdot kg^{-1}$ NO_3-N equates to $\approx 20 \text{ lb/acre } NO_3-N$ in 6 inches of soil. Concentrations up to 13.4 $mg \cdot kg^{-1}$ NO_3-N were found in the Tens-60 treatment. The residual soil NO_3-N has a high probability of leaching from the sandy textured soils when the polyethylene mulch is removed after the growing season if a cover crop is not implemented.

Higher calculated irrigation rates did not significantly impact residual soil NO_3-N concentrations. $1.0 \times ET$, $1.5 \times ET$, and $2.0 \times ET$ generally had statistically similar inorganic N concentrations in all seasons at each depth (except Spring 2010). The lack of significant differences parallels yield responses for most seasons; no significant differences were observed in yield between $1.0 \times ET$, $1.5 \times ET$,

and $2.0 \times ET$ in all seasons except Spring 2009 and Spring 2010.

Conclusions

Yield generally indicated that treatment $0.5 \times ET$ was the appropriate calculated irrigation regime for optimum yields with minimal irrigation inputs. Treatment Tens-40 also provided sufficient irrigation for optimum yields. Soil data at 0 to 10 inches generally exhibited an inverse relationship to yield; greater yields resulted in less residual soil NO_3-N . All treatments provided sufficient N to plants according to plant status measurements. The use of a tensiometer as a real-time field measurement with an optimal reading of -40 kPa is an advantageous instrument, and can protect plants from less than adequate irrigation rates that may decrease yields.

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